η photoproduction off the neutron at GRAAL:
Evidence for a resonant structure at W = 1.67 GeV

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New (preliminary) data on η photoproduction on the neutron are presented. These data reveal a resonant structure at W=1.67 GeV.

Meson photoproduction on the neutron may provide essentially new information regarding the spectrum of baryons. An example is given by a model[1] which exploits the SU(6) symmetry and assumes single-quark transitions from ground nucleons to the $[70, 1^-]$ supermultiplet. The model predicts only weak photoexcitation of the $D_{15}(1675)$ resonance from the proton target. Conversely, photon-neutron couplings of $D_{15}(1675)$ calculated in the framework of this approach are not small. Measurements of the relative strength of photoneutron/photoproton interaction are therefore an important testing ground for this (and others) theoretical approaches.

Another example is possible photoexcitation of the non-strange pentaquark state, which is associated with the second member of an antidecuplet of exotic baryons[2,3]. Evidence for the lightest member of the an-

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tidecuplet, the $\Theta^+(1540)$ baryon, is now being widely discussed[4]. It can be produced, in particular, by photoexcitation of the nucleon. However, exact $SU(3)_F$ would forbid the proton photoexcitation into the proton-like antidecuplet member. The chiral soliton model predicts that photoexcitation of the non-strange pentaquark has to be suppressed on the proton and should occur mainly on the neutron, even after accounting for $SU(3)_F$ violation[5]. Estimates of the mass and width of the non-strange pentaquark are ambiguous. As initial input, the mass was used to be 1.71 GeV[2], with the width estimated $\sim$ 40 MeV. More recent evaluation of the chiral soliton approach led to the range of $1.65 - 1.69$ GeV[6]. In the di-quarks approach[3], the mass of the pentaquark with hidden strangeness is quoted about 1.7 GeV. Modified partial wave analysis of the πN scattering[7] suggests two possible candidates, at 1.68 GeV and/or at 1.73 GeV, with the total width about 10 MeV and the partial width for πN decay mode less than 0.5 MeV. Thus, photo-neutron excitation data, and their comparison with photo-proton excitation, may be important both in establishing existence of pentaquarks and in discriminating between different theoretical concepts. Among other reactions, η photoproduction has been suggested as particularly sensitive to the manifestation of the non-strange pentaquark[2,3,5,7].

Up to now, η photoproduction on the neutron has been explored only in the region of the $S_{11}(1535)$ resonance from threshold up to W = 1.6 GeV[8,9,10]. Some of the previous experiments[8] were limited to inclusive measurements detecting only the outgoing η. In exclusive experiments[9,10], both the η and the recoil nucleon are detected. This makes it possible to discriminate between ηn and ηp final states and to select events corresponding to quasi-free kinematics.

A new exclusive measurement has been performed at GRAAL[11,12] using a deuteron target. Both quasi-free $\gamma n \to \eta n$ and $\gamma p \to \eta p$ reactions were explored simultaneously in the same experimental run under the same conditions and solid angle. Two photons from $\eta \to 2\gamma$ decay were detected in the BGO crystal ball[13]. Recoil neutrons and protons emitted at $\Theta_{lab} = 3 - 23°$, were detected in an assembly of forward detectors, which includes two planar multiwire chambers, a time-of-flight (TOF) wall made of thin scintillator strips, and a lead-scintillator sandwich TOF wall[14]. The latter detector adds the option of neutron detection with an efficiency of $\sim 22\%$. The momenta of the η and recoil nucleons were reconstructed from measured energies, TOFs and angles of outgoing particles.

As a first step, the identification of the ηn and ηp final states was achieved in a way similar to that used in the previous measurements[12] on the free proton. The η was identified by means of the invariant mass of

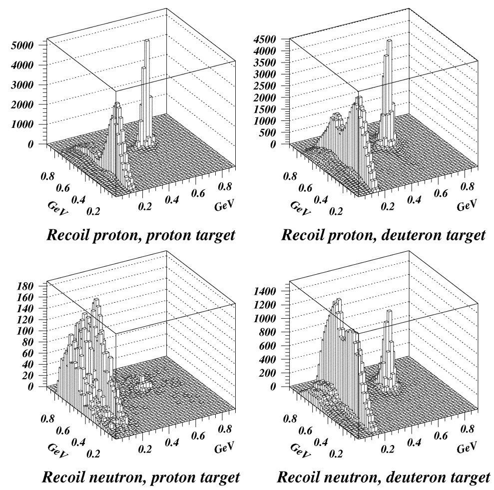

Figure 1. Bi-dimensional plots of invariant mass of two photons versus missing mass calculated from momenta of recoil nucleons for proton and deuteron targets.

two photons and its momentum was reconstructed from measured photon energies and angles. Then measured parameters of the recoil nucleon were compared with ones expected assuming quasi-free kinematics. Fig. 1 shows bi-dimensional plots of 2γ invariant mass versus η missing mass obtained in experimental runs with proton and deuteron targets. A good ηp signal was obtained with the proton target, while only few ηn events were detected in this run. Signals of both final states clearly appear with the deuteron target.

In case of a photon interaction with the nucleon bound in a deuteron target, event kinematics is "peaked" around that one on the free nucleon. Fermi motion of the target nucleon changes the effective energy of photon-nucleon interaction and affects parameters of outgoing particles. Part of events may suffer from re-scattering and final-state interaction[15]. The goal of the second-level selection was to reduce re-scattering events, the remaining background (mostly from $\gamma d \to \eta\pi NN$), and those events whose kinematics are strongly distorted by Fermi motion. Additional cuts on the recoil nucleon missing mass $M(\gamma N, \eta)$ and ΔTOF have been applied. Those events in which the detection of two photons and the recoil nucleon was accompanied by the detection of any low-energy particle(s) in the 4π GRAAL detector, have been eliminated from the analysis.

The strategy at this stage was to study the dependence of spectra of selected events on cuts. Two criteria of quality of the selection procedure have

been exploited: (i) distribution of Fermi momentum of the target neutron reconstructed as "missing momentum" with small correction on binding energy; (ii) difference of the center-of-mass energy W calculated from the momentum of the initial-state photon and assuming the target nucleon at rest, and the center-of-mass energy deduced as the invariant mass of the final-state η and the neutron. The first quantity includes uncertainties due to Fermi motion and is "peaked" around the real center-of-mass energy of photon-nucleon interaction. The ηn invariant mass is not affected by Fermi motion but includes large uncertanties (50 – 80 MeV, FWHM) due to detector resolution.

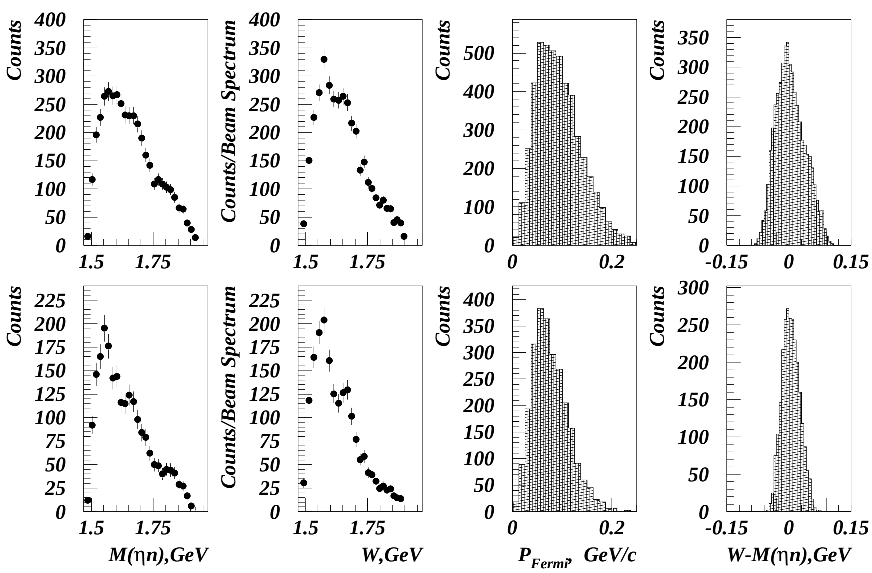

Figure 2. Spectra of center-of-mass energy, calculated as invariant mass of final-state η and the neutron (first column), from the energy of the itial-state photon and assumimng the target neutron in the rest (second column), Fermi momentum of the target neutron (third column), and difference between initial-state and final-state center-of-mass energies (fourth column) after different cuts (see text).

In the upper row of Fig. 2, the final-state (first column) and initial-state (second column) W spectra obtained with the first-level cut are shown. Both of them indicate a wide bump in the region 1.6 – 1.7 GeV. The Fermi momentum (third column) exhibits a broad distribution. Plots in the lower row correspond to final cuts. Both final and initial-state spectra are similar and show an enhancement of the $S_{11}(1535)$ resonance below 1.6 GeV. The bump near 1.67 GeV observed in the previous spectra, becomes more

narrow and well-pronounced. The Fermi-momentum spectrum is more compressed and has its maximum near 0.05 GeV/c, as expected for quasi-free events.

Evolution of spectra in Fig. 2 suggests that most of events rejected by the second-level cuts either originate from re-scattering and final-state interaction or strongly suffer from Fermi motion. On the contrary, events shown in lower-row plots, are more "clean". They correspond to quasi-free photoproduction, and the distortion due to Fermi motion is reduced. The latter fact makes it possible to clearly reveal the structure at 1.67 GeV. These events were found suitable for the further analysis.

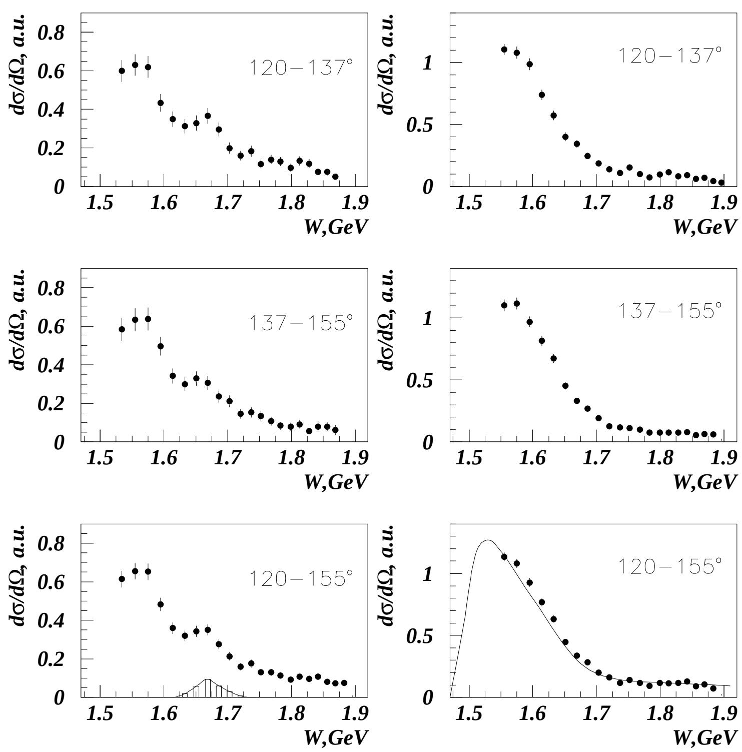

Figure 3. Preliminary quasi-free ηn(left) and ηp(right) photoproduction cross sections (dark circles). Solid line indicates E429 solition of the SAID $\gamma p \rightarrow \eta p$ partial wave analysis[17]. Dashed area shows simulated contribution of a narrow state at W=1.675 GeV.

Preliminary quasi-free ηn and ηp photoproduction cross sections are shown in Fig. 3. The normalization has been done by comparing quasi-free proton data and the E429 solution of the SAID $\gamma p \rightarrow \eta p$ partial wave

analysis[17] for η photoproduction on the proton which was obtained from the fit to all available data including recent data from GRAAL[11,12], JLab[18], and SAPHIR[19]. Such normalization made it possible to avoid ambiguities related to the fact that some of the events are lost due to the re-scattering and final-state interaction. Above 1.55 GeV, a reasonable coincidence in the shape of the cross sections has been obtained. At lower energies, re-scattering and final-state interaction become more significant and play a dominant role near threshold[15]. Error bars shown in Fig. 3 correspond to statistical uncertainties only. The present normalization uncertainty of 12% originates mostly from the quality of simulations of quasi-free processes and from uncertainties in the neutron detection efficiency.

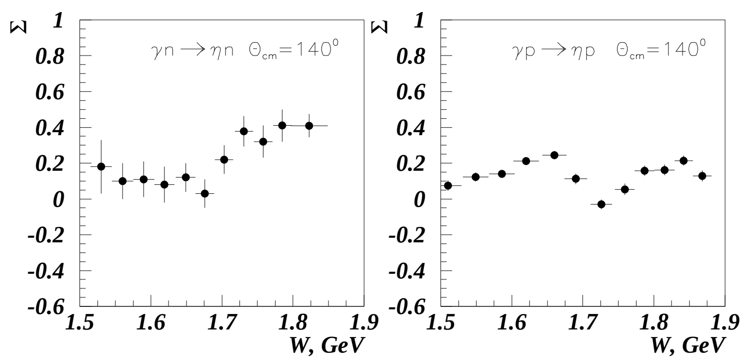

Figure 4. Beam asymmetry Σ for ηn(left) and ηp(right) photoproduction.

At W below 1.6 GeV, both cross sections exhibit bumps due to the $S_{11}(1535)$ resonance. At higher W, an additional structure clearly appears for the neutron and is not seen on the proton. Remarkably, beam asymmetry Σ (Fig. 4) shows pecularities at the same energies. In the region of $S_{11}(1535)$ resonance, Σ ranges around 0.2 and is nearly the same for the neutron and the proton. In the region 1.65 – 1.73 GeV, there are step-like changes. The trends of these changes are opposite: for the proton, the asymmetry becomes almost 0, while for the neutron it rises up to 0.4. It is worth noting that beam asymmetry is more sensitive to the non-dominant contributions than cross section since it is given by the interference of helicity amplitudes H_i[16] corresponding to four possible helicity states of the target and recoil nucleon:

$$d\sigma/d\Omega \sim \mid H_1 \mid^2 + \mid H_2 \mid^2 + \mid H_3 \mid^2 + \mid H_4 \mid^2$$

$$\Sigma \sim Re(H_1 H_4^* - H_2 H_3^*)$$

Both the observed peak in the cross section on the neutron and corresponding changes in beam asymmetry might be an indication that one of the nucleon resonances has much stronger photocoupling to the neutron than to the proton. In Fig. 3, the simulated contribution of a narrow (10 MeV) resonance state with a mass of 1.675 GeV is shown. Such a state appears in the cross section as a 40 MeV wide peak due to Fermi motion of the target nucleon. The shape of the simulated peak fits quite well the shape of the peak observed in the cross section on the neutron.

Therefore, this peak may be a signal of a relatively narrow state. Potentially, this state looks promising as a candidate for the non-strange pentaquark. The feature of strong photocoupling to the neutron agrees with the prediction of the chiral soliton model[5]. On the other hand, one cannot exclude that the observed peak is a manifestation of one of the known resonances, in particular, the $D_{15}(1675)$, as is suggested by the single-quark transition model[1]. A crucial task is to "unfold" the cross-section and beam-asymmetry data from Fermi motion, in order to achieve a reliable estimate of the width of this state. As a further step, a partial wave analysis will be needed to fix its quantum numbers.

It is worth to add that the kaon photoproduction has been quoted as well to be particularly sensitive to the signal of the non-strange pentaquark[2,3,5,7] as well. Very preliminary indications on a state at 1.72 GeV have been obtained in $\gamma n \to K^0_s\Lambda$ and $\gamma n \to K^+\Sigma^-$ reactions[20], in production of $K^0_s\Lambda$ final state in $Au + Au$ collision[21], and in $pp \to K^+\Lambda p$ reaction[22].

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References

1. V. Burkert *et al.*, *Phys. Rev. C* **67**, 035204 (2003).
2. D. Diakonov, V. Petrov, and M. Polyakov, *Z. Phys. A* **359**, 305 (1997).
3. R. Jaffe and F. Wilczek, *Phys. Rev. Lett.* **91**, 232003 (2003); arXiv:hep-ph/0307341.
4. T. Nakano, to be published in Proceedings of Workshop on Physics of Excited Nucleons NSTAR2004, Grenoble, March 24 - 27, 2004; V. Burkert, to be published in the same Proceedings.
5. M. Polaykov and A. Rathke *Eur. Phys. J A* **18**, 691 (2003); arXiv:hep-ph/0303138.
6. D. Diakonov and V. Petrov, *Phys. Rev. D* **69**, 094011 (2004); arXiv:hep-ph/0310212

7. R. Arndt *et al.*, *Phys. Rev. C* **69**, 0352008 (2004); arXiv:nucl-th/0312126. 297 (1997);
8. B. Krushe *et al.*, *Phys. Lett.* **B358**, 40 (1995).
9. V. Heiny *et al.*, *Eur. Phys. J. A* **6**, 83 (2000); J. Weiß *et al.*, *Eur. Phys. J. A* **16**, 275 (2003), arXiv:nucl-ex/0210003.
10. P. Hoffman-Rothe *et al.*, *Phys. Rev. Lett.* **78**, 4697 (1997).
11. F. Renard *et al.*, *Phys. Lett.* **B528**, 215, 2002.
12. J. Ajaka *et al.*, *Phys. Rev. Lett.* **81**, 1797, 1998.
13. F. Ghio *et al.*, *Nucl. Inst. and Meth. A* **404**, 71, 1998.
14. V. Kouznetsov *et al.*, *Nucl. Inst. and Meth. A* **487**, 128, 2002.
15. A. Baru, A.Kudryavtsev, and V. Tarasov, *Phys. Atom. Nucl.* **67** 743, 2004, arXiv:nucl-th/0301021; A. Sibirtsev, S. Schneider, and C. Elster, *Phys. Rev. C* **65**, 067002 (2002), arXiv:nucl-th/0203039; A. Fix and H. Arenhovel, *Phys. Rev. C* **68**, 44002 (2003), arXiv:nucl-th/0203039; and references therein.
16. Definitions of helicity amplitudes are available in W.-T. Chiang and F. Tabakin, *Phys. Rev. C* **55**, 2054 (1997); R. A. Arndt *et al.*, *Phys. Rev. C* **42**, 1853 (1990).
17. R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, in progress, http://gwdac.phys.gwu.edu.
18. M. Dugger *et al.*, *Phys. Rev. Lett.* **89**, 222002 (2002).
19. V. Crede *et al.*, arXiv:hep-ex/0311045.
20. V. Kuznetsov for the GRAAL Collaboration. Talk at Workshop "Pentaquark states: structure and properties", Trento, Italy, February 10 - 12, 2004. http://www.tp2.ruhr-uni-bochum.de/talks/trento04/index.html.
21. S. Kabana for the STAR Collaboration. Talk at 20th Winter Workshop on Nuclear Dynamics, Jamaica, March 15 - 20, 2004. arXiv:hep-ex/0406032.
22. W. Eyrich for the COSY-TOF Collaboration. Talk at the International Workshop "Pentaquark04", Spring-8, Japan, July 20 - 23, 2004. http://www.rcnp.osaka-u.ac.jp/penta04/.